Distributed Recharge and Groundwater Flow Modeling in an Over-Exploited Aquifer*

Coupling HYDRUS-1D and 3D Groundwater Flow in the California Central Valley

Sustainable Agricultural Water Systems | USDA-ARS

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USDA Agricultural Research Service

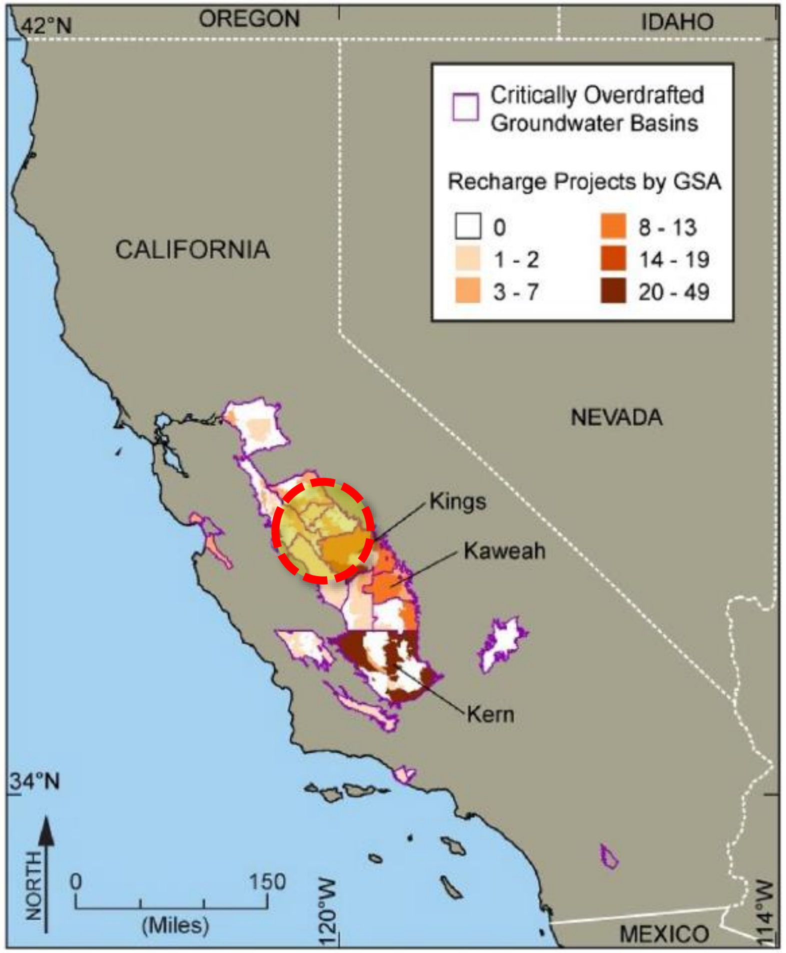
Objectives

* Develop and implement a computationally efficient **watershed model** (or models) to predict impacts of **MAR (Climate change)** on **water quantity** and **quality**.

1. Develop a realistic conceptual model to accurately determine water balance components.
2. Evaluate the current state and dynamics of water systems.
3. To quantify the potential impact of future climatic conditions and water management and conservation practices

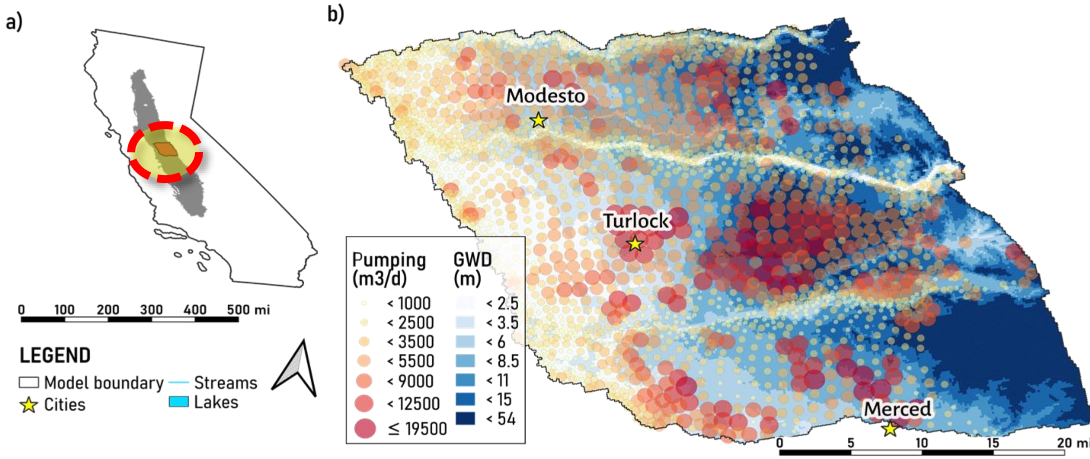
Outline*

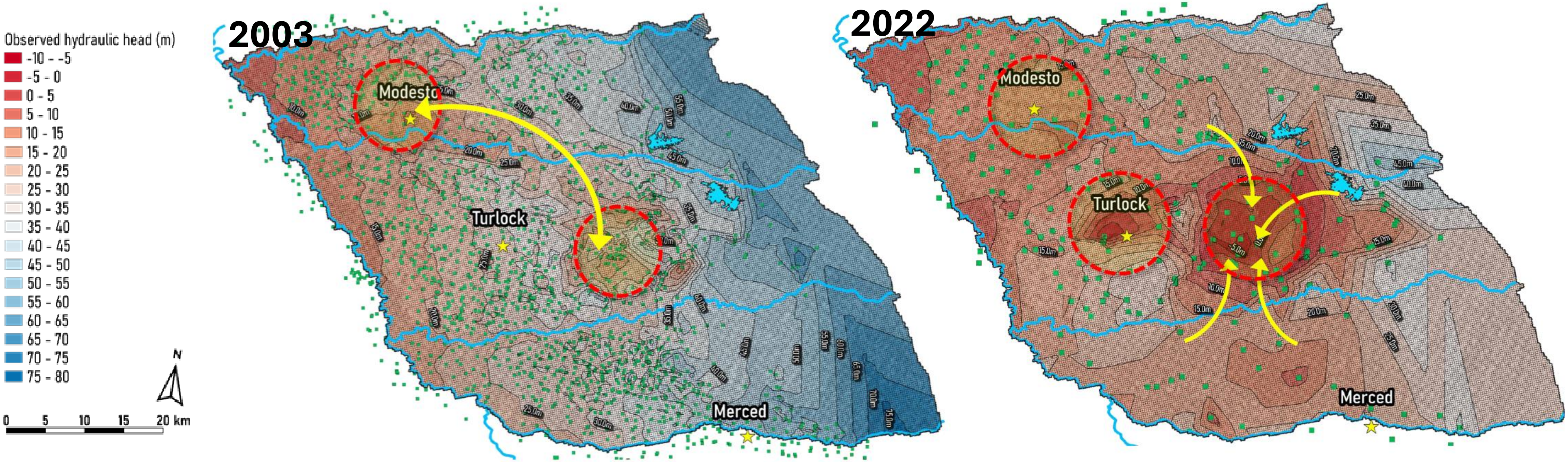
* *i)* Objectives and modeling approaches
* *ii)* Model Domain
* *iii)* Hydrogeological Recharge Unit (HGRU)
    a) Spatiotemporal variability
    b) Conceptual model structure
* *iv)* HYDRUS – MODFLOW coupling
* *v)* Results
    a) Distributed recharge
    b) Distributed transit time
    c) Water level dynamics and model accuracy
    d) Particle tracking and age of water
* *vi)* Conclusion



Study Area

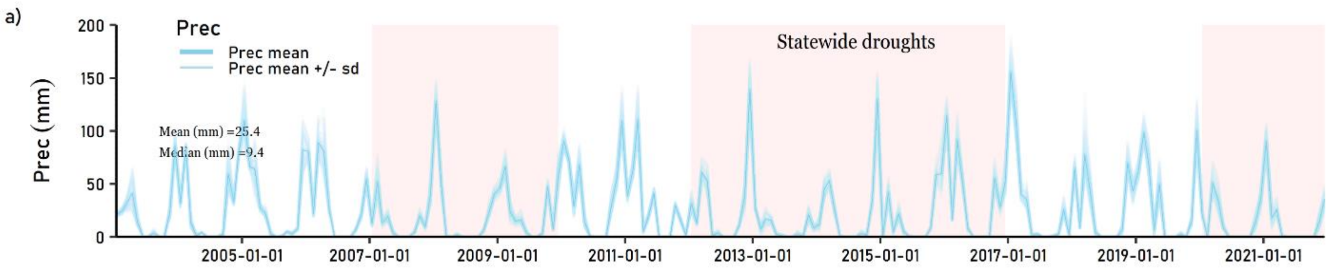
- Turlock, Modesto and part of Merced subbasins.
- Covers approximately 7,200 km², encompassing five GSAs.
- It extends about 74.4 km along the valley axis and 96.9 km towards the foothills of the Sierra Nevada.





Study Area

- Evapotranspiration and precipitation conditions across model domain



- The region experiences frequent and prolonged drought
    1. heavily reliant on groundwater
    2. limited surface water resources

- Average annual precipitation of around 315 mm (150 to 635 mm).

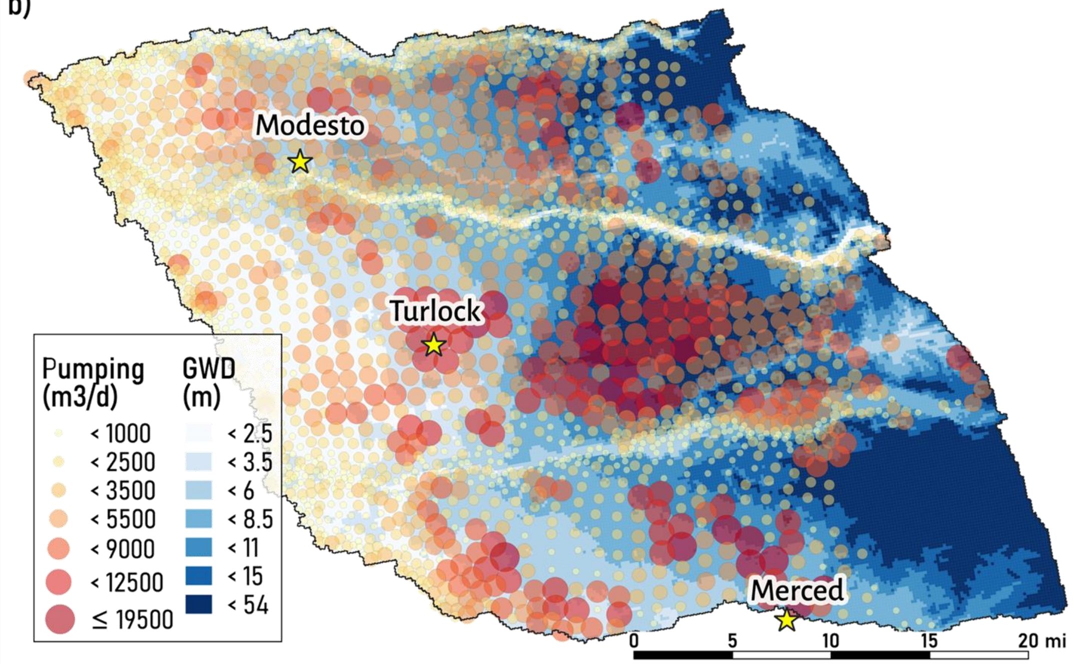
- Average monthly deficit (i.e., difference between actual evapotranspiration and precipitation) is 30.3 mm.

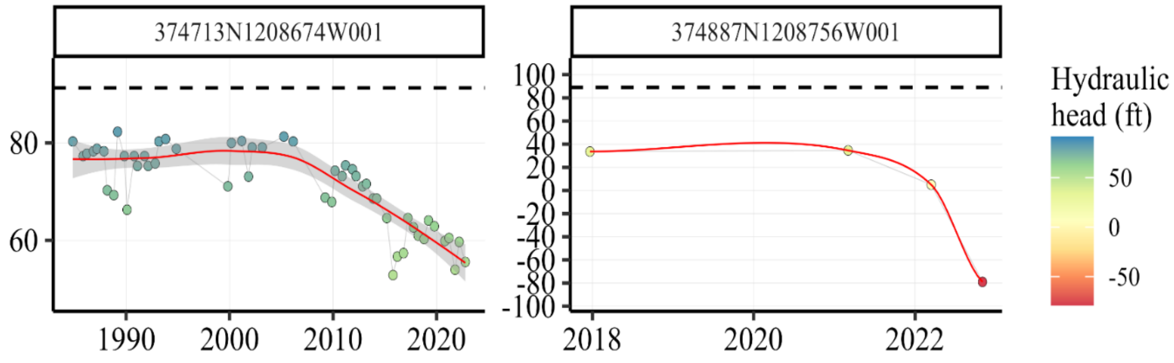
- Increasing trend on depth to groundwater table over time.

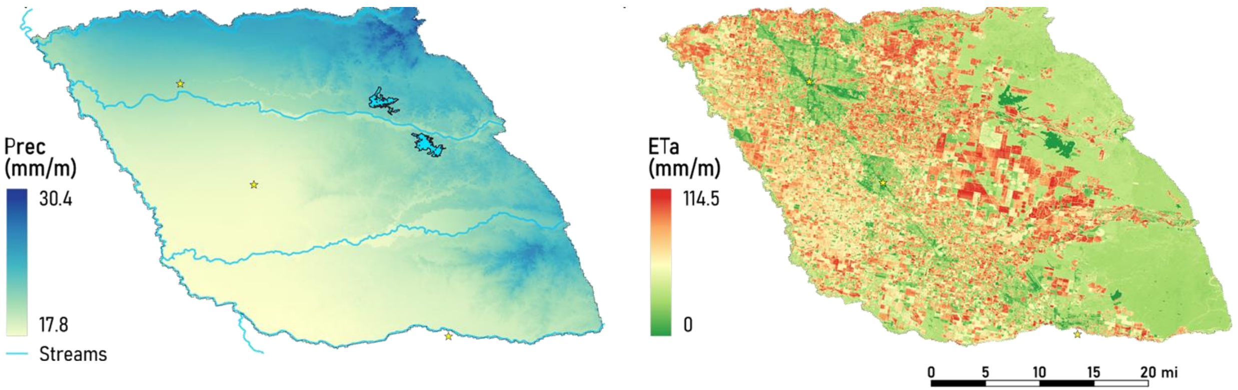
Study Area

- Groundwater subbasins are highly depleted but not as sever as some of the southern subbasins.

b)







- Critically over drafted groundwater basins
- Water level decline has accelerated after 2000
- Precipitation shows southwest gradient
- Significant variability in ETa

Study Area

- Over abstraction resulted in accelerated drawdown of the water table.

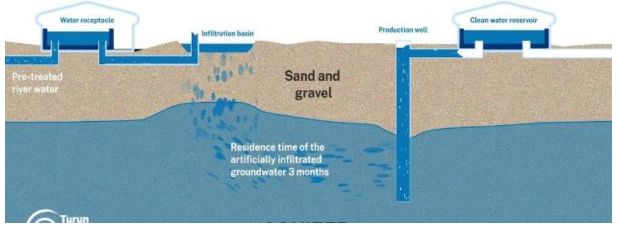
Well type	GSP	Total number of wells	Percentage of partially dewatered wells	Percent of fully dewatered wells	Estimated range of people affected
Domestic wells	Merced	1730	15%	27%	756-5664
	Modesto	939	4%	1%	21-468
	Turlock	1571	7%	3%	123-1308
Public supply wells	Merced	89	6%	62%	-
	Modesto	199	4%	1%	-
	Turlock	153	20%	15%	-

- More frequent occurrences of dry wells, particularly for domestic users, and
- Increased energy costs for landowners (pump from deeper depths)
- Highlights the urgent need for effective groundwater management strategies.

Bostic et al. (2023)

Modelling Approach

- HYDRUS 1D-MODFLOW Coupling
- Physics based unsaturated flow modeling and surface to groundwater interaction

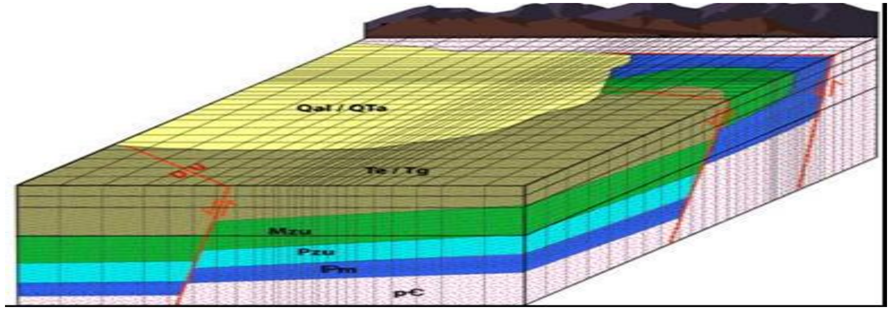


MAR and climate scenarios

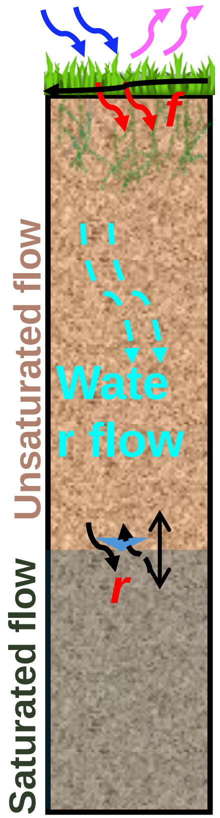
Data collection and evaluation → HYDRUS 1D + MODFLOW → Integrated model optimization → Results interpretation

Pumping wells, evapotranspiration, river stages

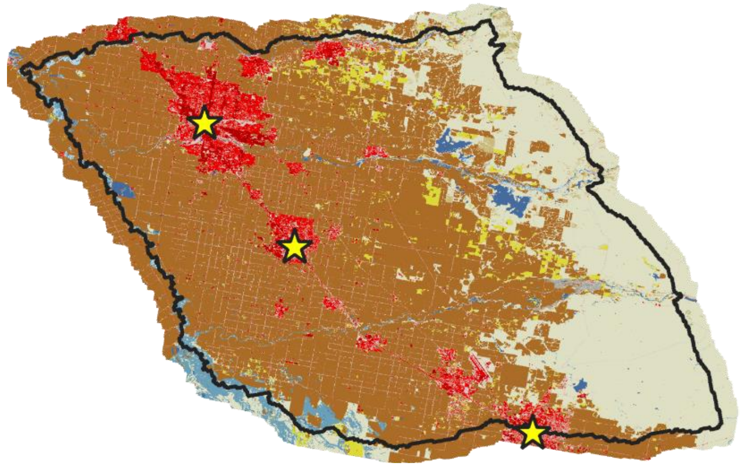
- Sediment Texture = Borehole lithology



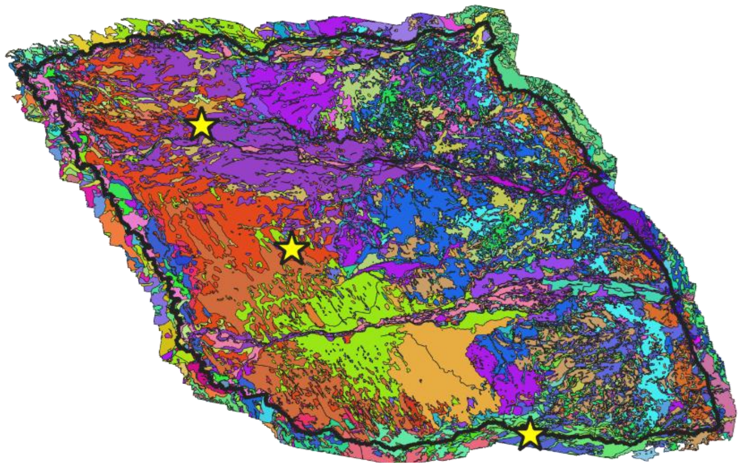
Hydrogeological Recharge Units (HGRU)



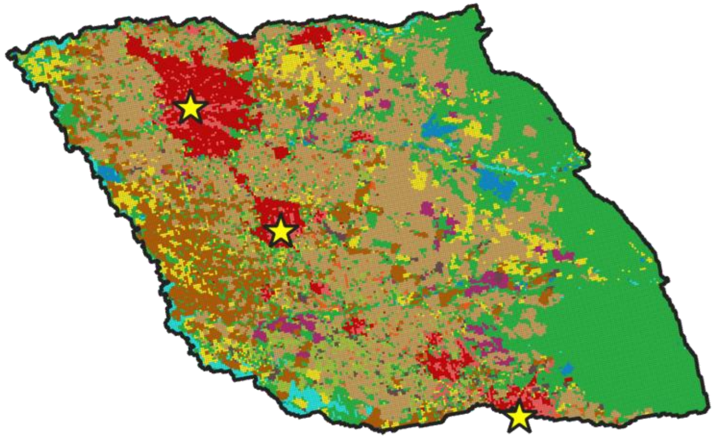
Land cover classes



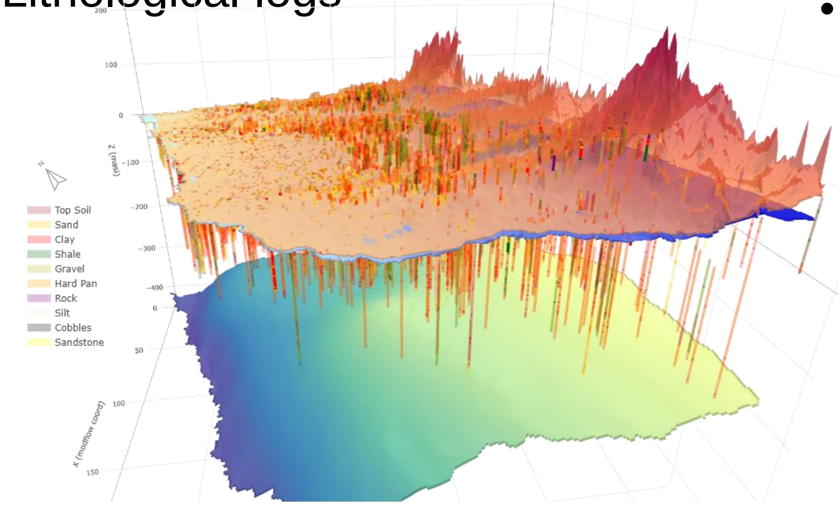
Dominant soil series



Crop types

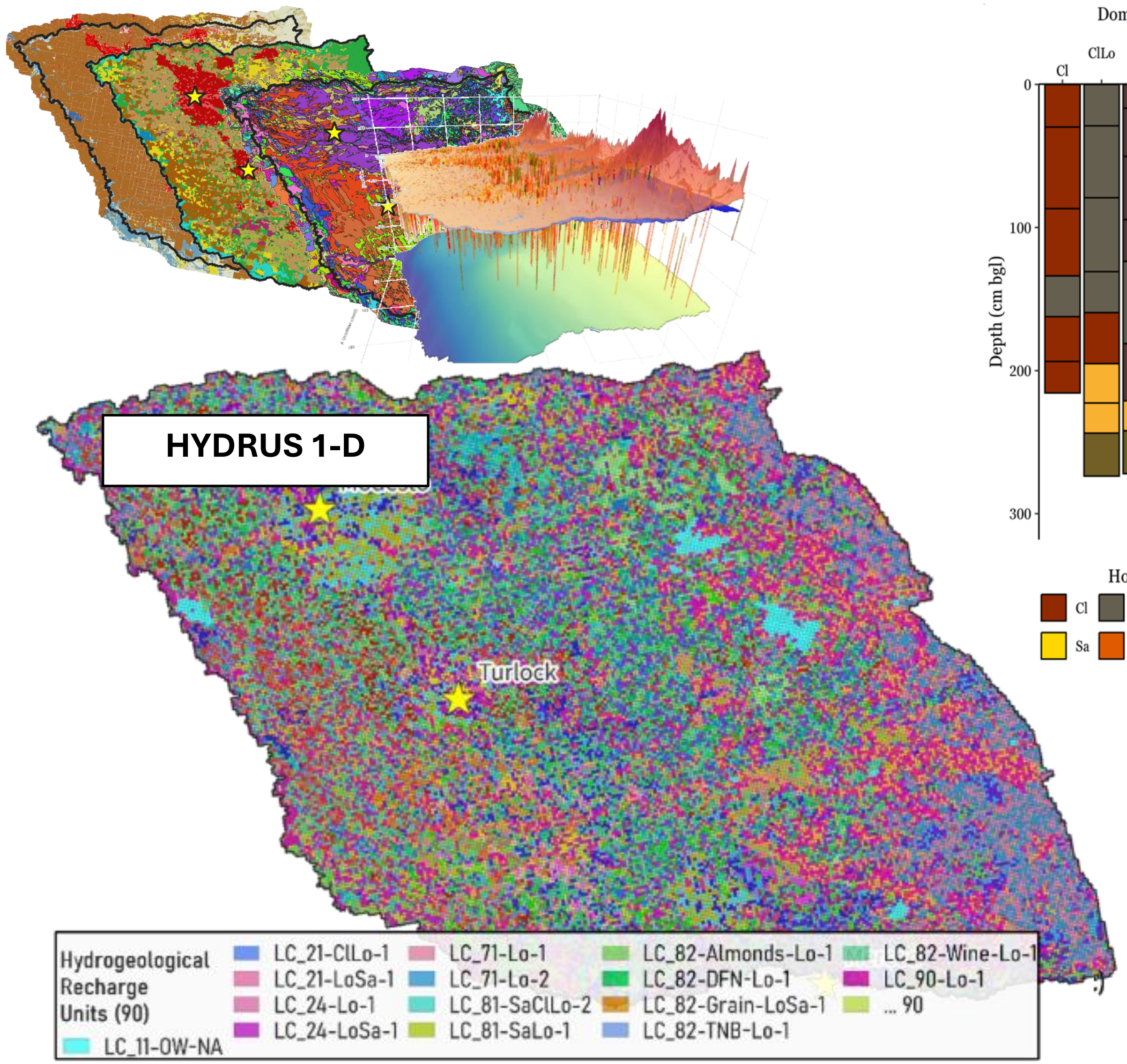


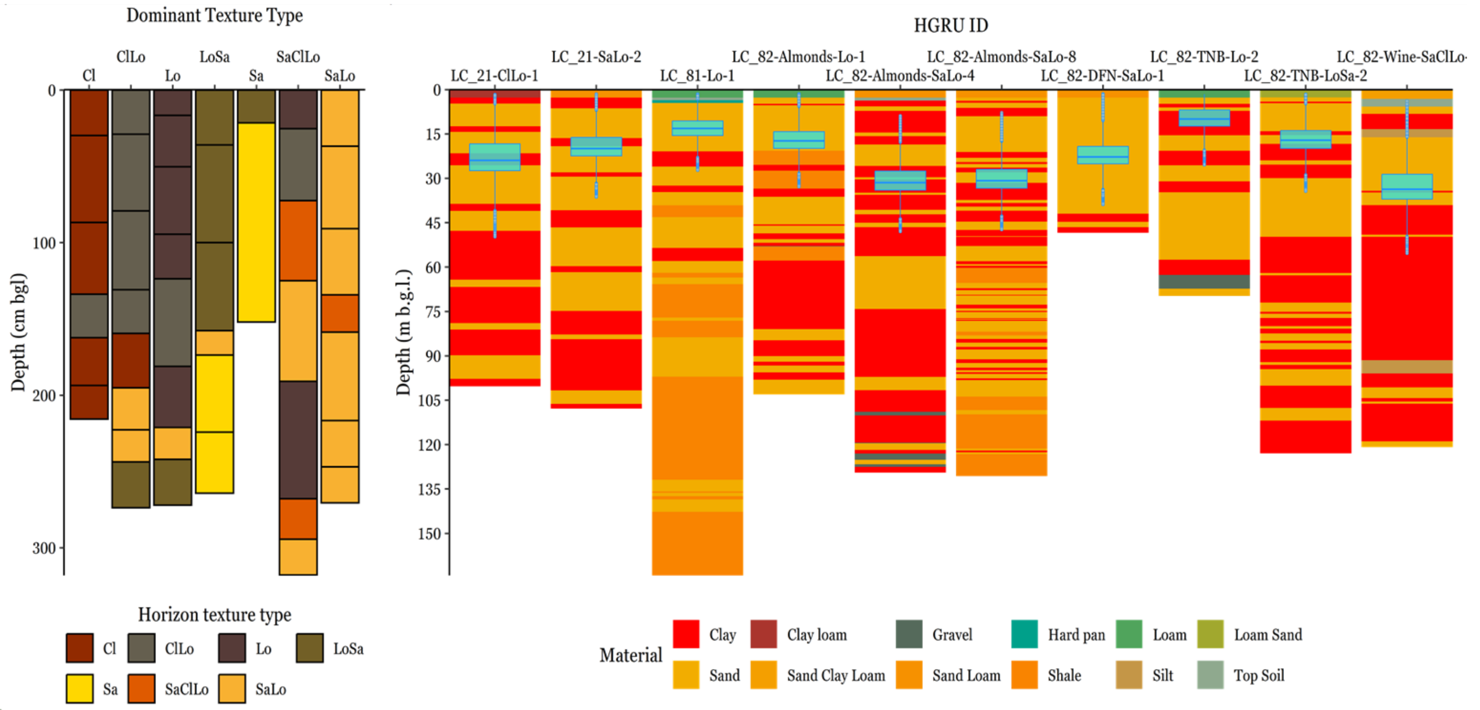
Lithological logs



- Constructed to identify the spatial variability in groundwater recharge across the model domain
- Groundwater recharge was defined as the flux effectively reaching the groundwater table at every time-step.
- HGRU is a unique profile category representing all model domain cells with similar LC, DSS, CT, and BL characteristics in the overlying landscape and in the vadose zone.

Hydrogeological Recharge Units (HGRU)

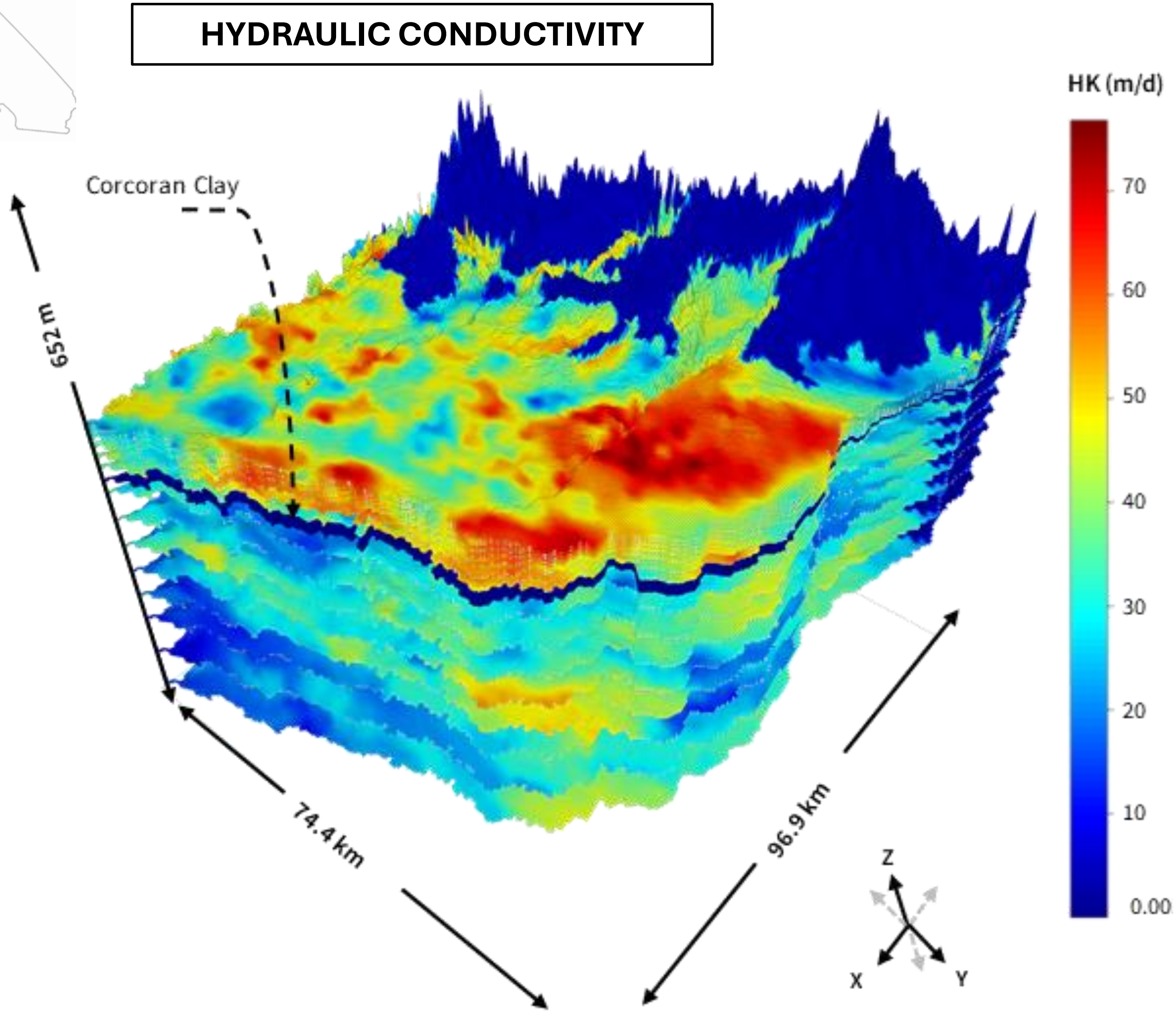




Randomly selected Hydrogeological Recharge Units (HGRU)

- A total of 86 HGRUs were defined across the MODTUR domain.
- The number of the HGRUs depend on the level of details required and availability of the computing resources.

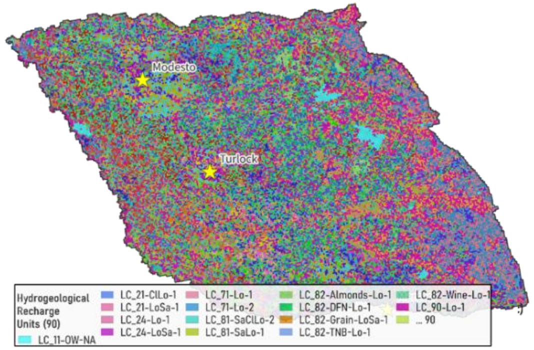
Three-dimensional Groundwater flow model



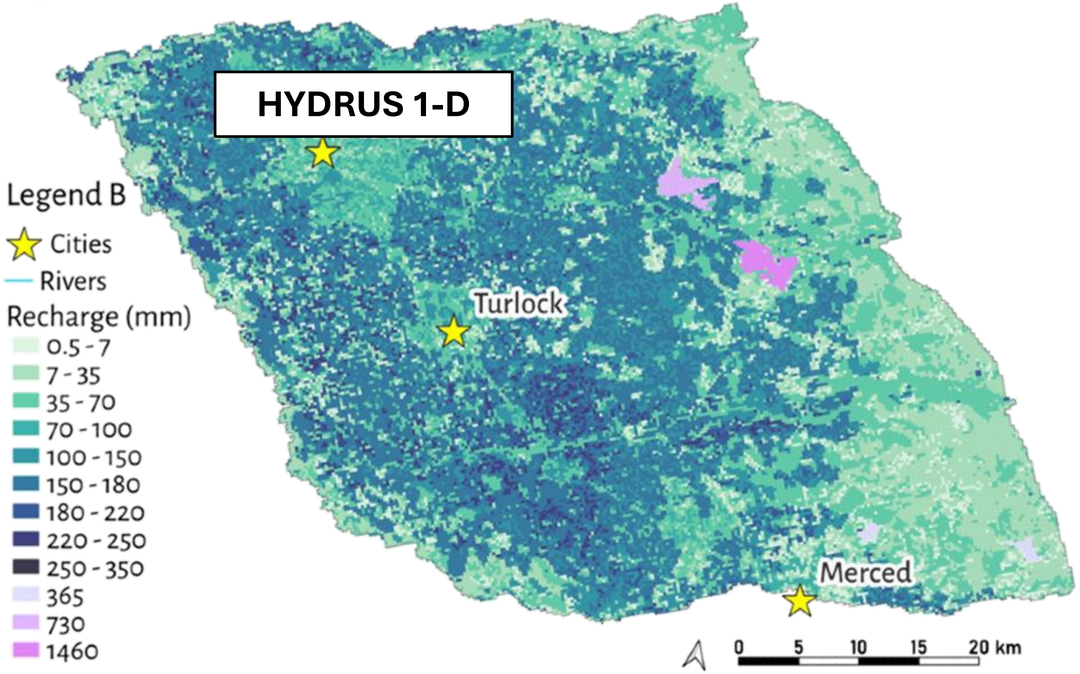
- The groundwater flow model captures the geometry, hydrologic, and hydrogeologic properties of the model domain.
- Hydraulic conductivity values derived by percentage of coarse-grained materials following the weighted arithmetic and power means method.

Results

- Recharge values from 2003 to 2022

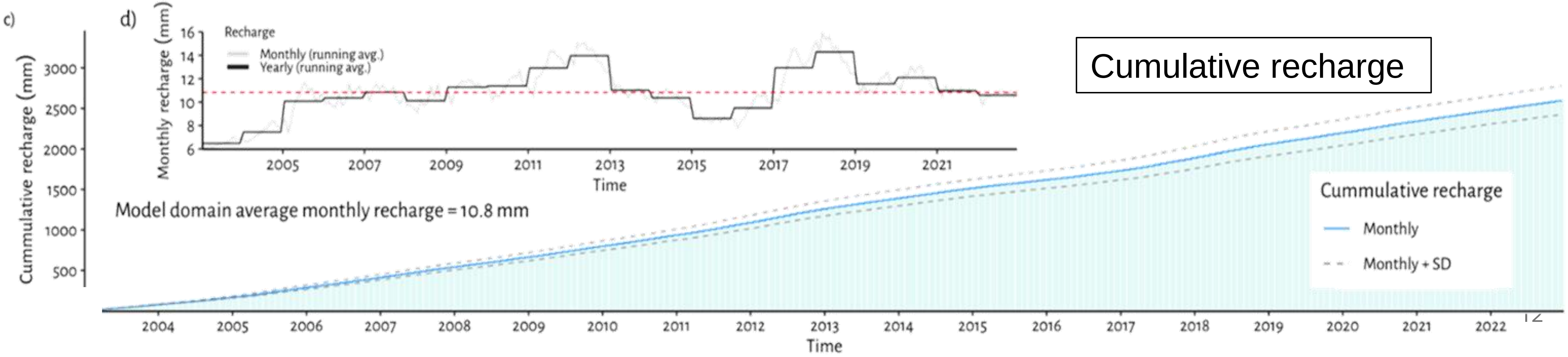


Annual recharge (mm)



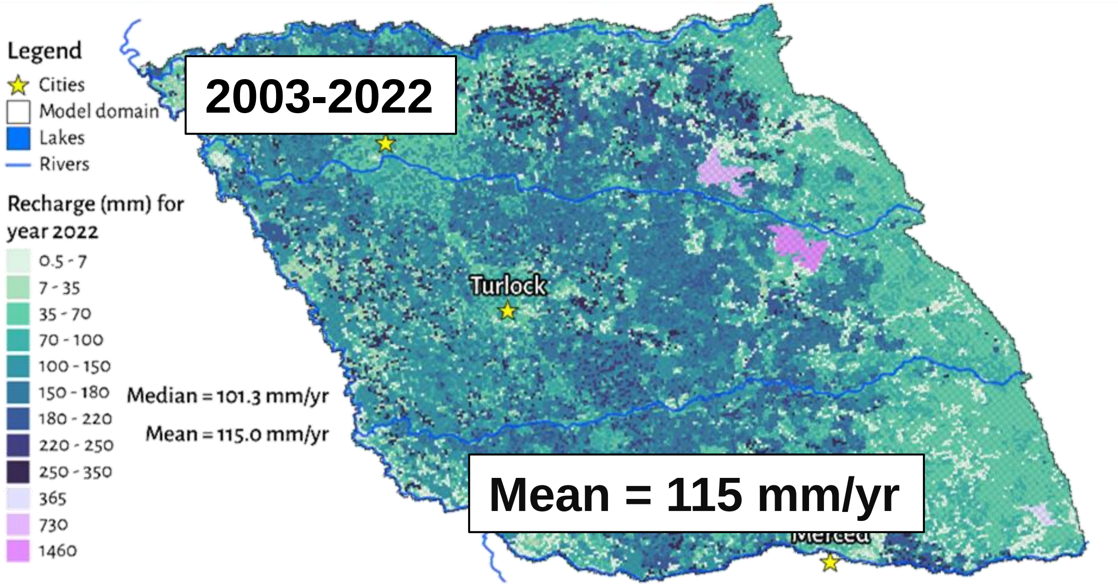
- Average monthly groundwater recharge across the MODTUR model domain is 10.8 mm
- Recharge rates show significant spatial and seasonal variations
- A large part of the MODTUR model domain (31%) was classified as crops in the category of “LC_82-Almonds”, spread over several soil and lithological classes.

Cumulative recharge



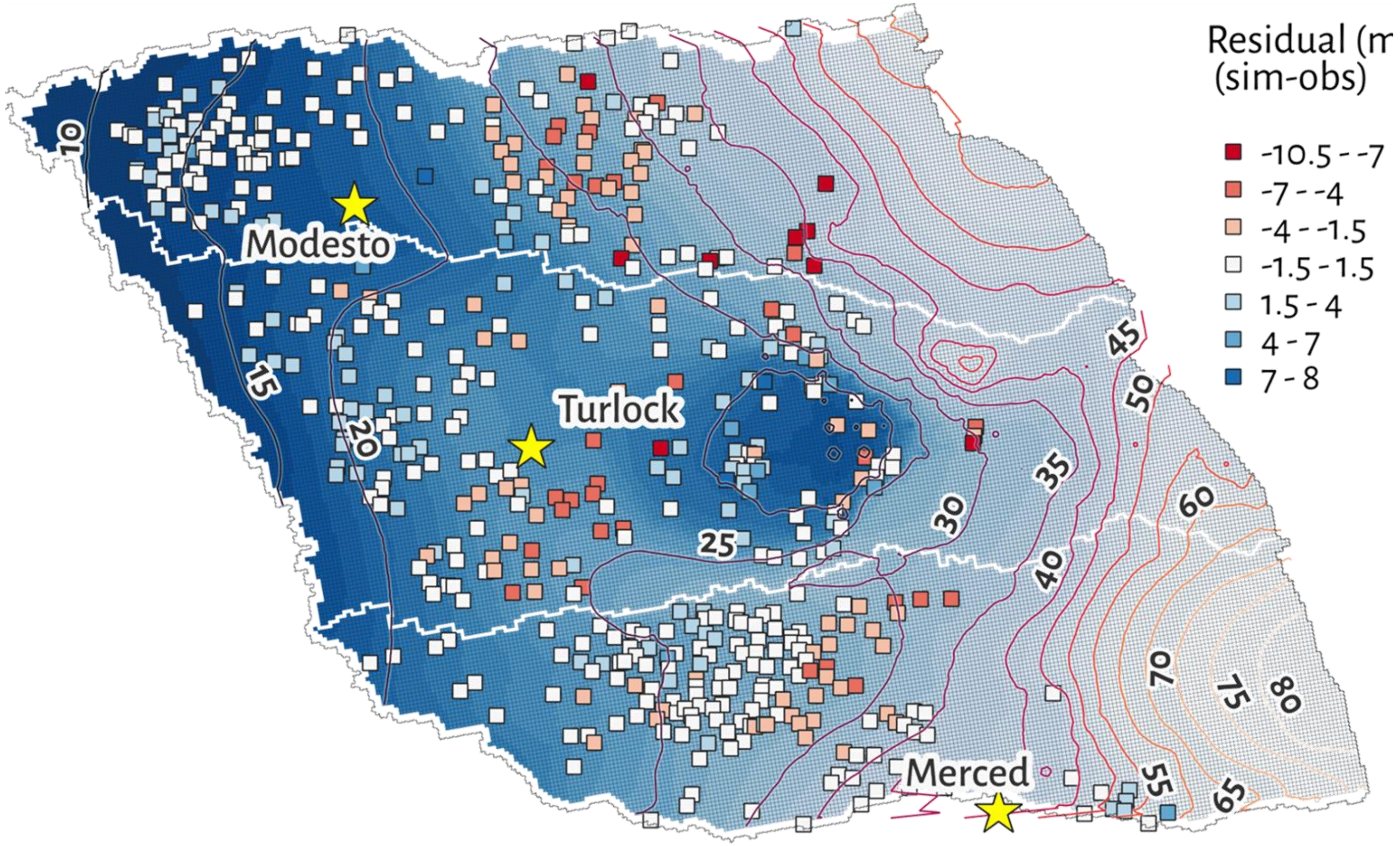
Results

- Spatially distributed recharge (left) and unsaturated zone residence time (right)

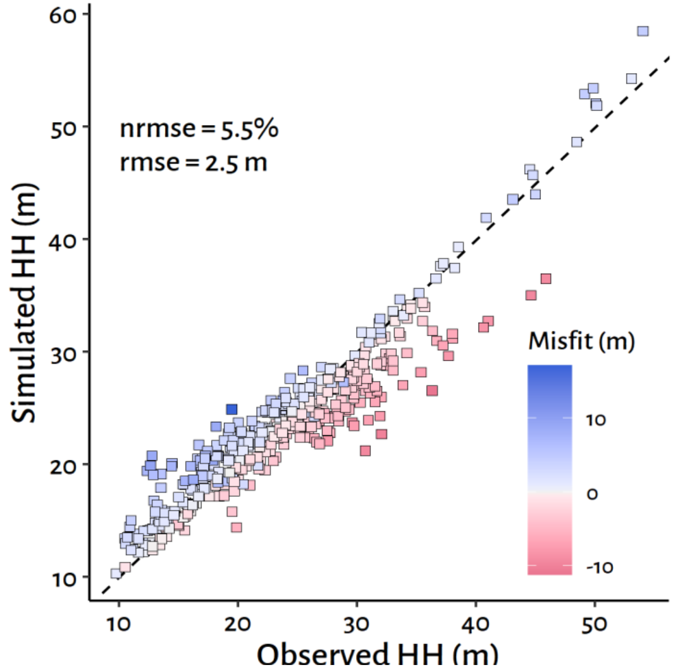


Results

- Steady-state hydraulic head distribution



Fair approximation to the observed groundwater heads

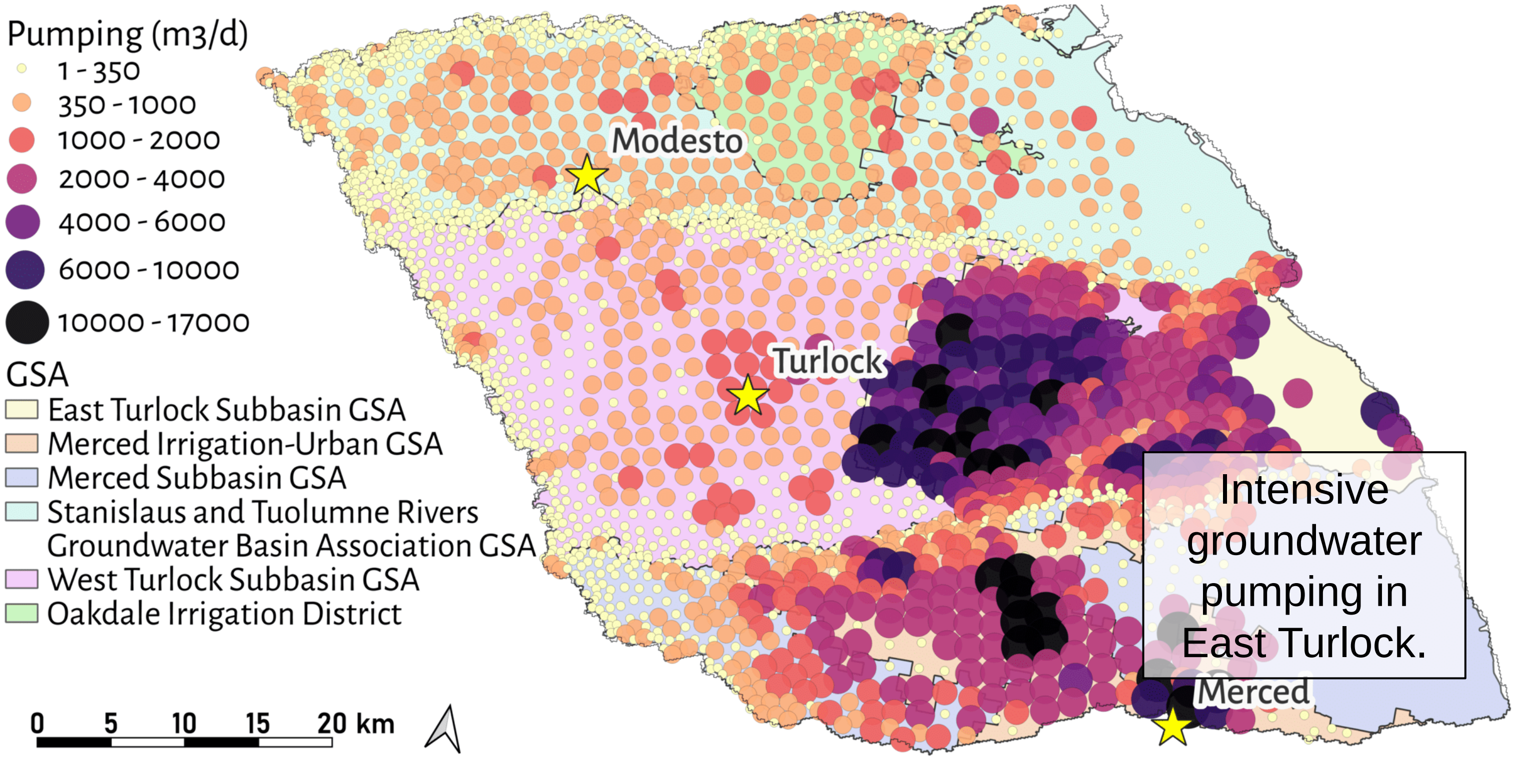


- The model captured the developing cone of depression in the center of East Turlock (± 4m),
- The western boundary shows an acceptable agreement between simulated and observed hydraulic heads. (± 1.5 m),
- Model errors increases around the periphery of the cone of depression.

Results

- Steady-state hydraulic head distribution

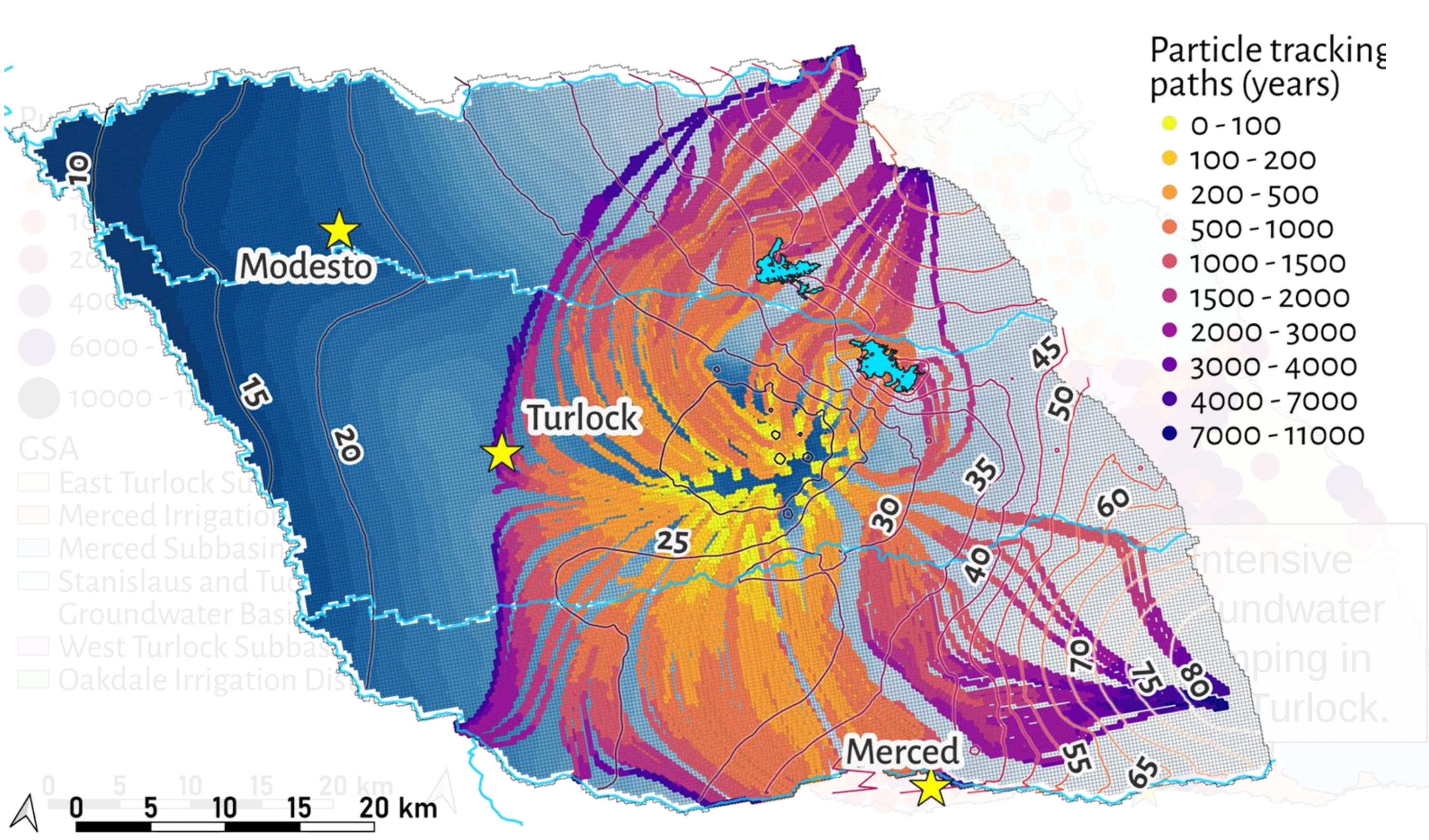
- Initial pumping values were adopted from the C2VSim-FG model, where rates are determined with higher recharge estimates.
- Pumping values were included during calibration.



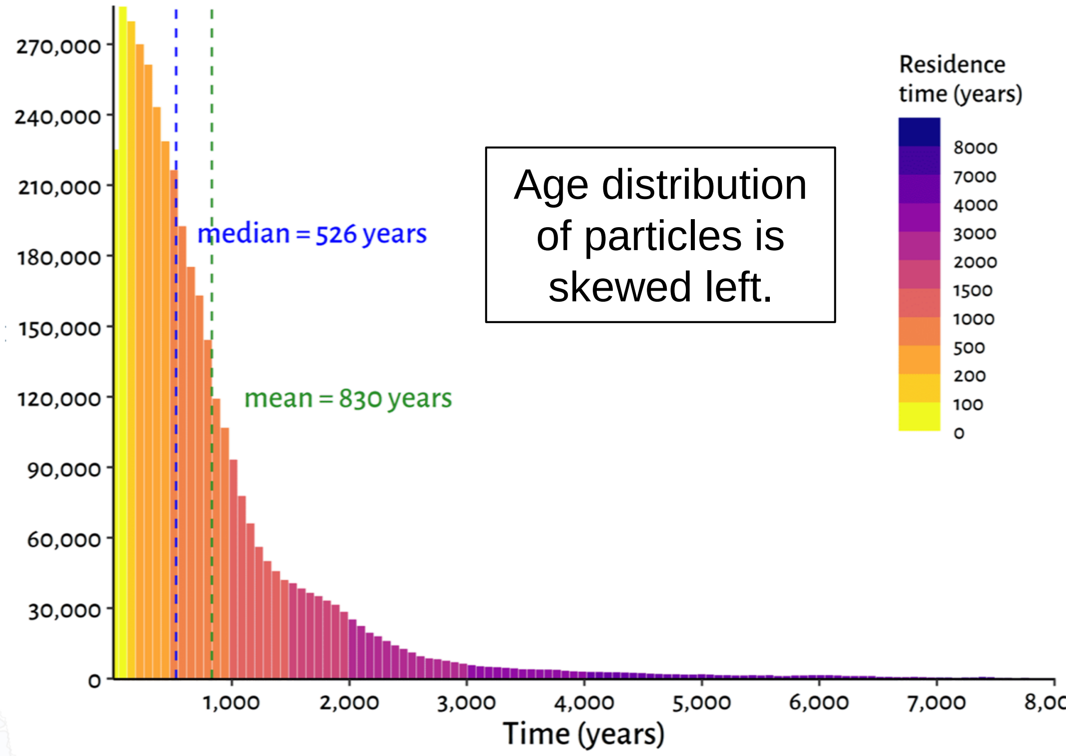
Results

- Steady-state advective transport

- Groundwater residence time: 2 years to 5,000 years (up to 8,000 years)



Particle back-tracking path lines



Histogram of ages, in years, of back-tracked particles including median and mean residence time values.

Conclusions

- The integration of **HYDRUS-1D** with a high-resolution 3D **MODFLOW** model improves understanding of **groundwater dynamics, recharge, and pumping** processes.
- The **Richards-equation** approach highlighted **spatial variability in recharge** and **residence times** through the thick unsaturated zone.

- **Intensive pumping** in East Turlock caused a **cone of depression**, which is altering the regional **groundwater flow system**.
- **Particle tracking** revealed **varied residence times** and **transit times** to groundwater, with faster circulation near pumping and slower paths in peripheral areas.

- **Targeted recharge** in high-recharge zones like almond and walnut fields is key for **groundwater sustainability** and **effective GSPs**.
- This modeling approach strikes a balance between **complexity** and **practical application**, supporting **GSAs**.

Thank you!

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